THE BR2-MATERIAL TESTING REACTOR AND ITS MAJOR CONTRIBUTION TO THE REACTOR MATERIAL, FUEL AND SAFETY RESEARCH

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ABSTRACT

The BR2 was shutdown at the end of June 1995 for a programme of extensive refurbishment after more than 30 years utilisation. The beryllium matrix was replaced and the aluminium vessel inspected and requalified for the envisaged 15 years life extension. Other aspects of the refurbishment programme were aimed at reliability and availability of the installations, safety of operation and compliance with modern safety standards.

The reactor was restarted in April 1997.

This paper deals with aspects of this refurbishment in general as well as the ongoing experimental projects in the areas of reactor material, fuel behaviour and safety research.

INTRODUCTION

The BR2 reactor of the Belgian Nuclear Research Centre (SCK•CEN) at Mol, Belgium, was put into operation in January 1963.

This Materials Testing Reactor is acknowledged as one of the most powerful of its type in Europe and even in the world.

The reactor plays an essential role in the national and international programmes related to:

- the safety of nuclear reactors, plant lifetime and ageing of components;
- the safety of nuclear fuels, the increase of their burn-up and the use of MOX fuels;
- the evolution and assessment of safety problems;
- production activities related to medical and industrial application.

The capabilities and the design of the BR2 are particularly well adapted to these R&D options:

- a core with a central vertical 200 mm diameter channel, with all its other channels inclined to form a hyperboloidal arrangement around it. This geometry combines compactness leading to high fission power density, with easy access at the top and bottom covers, allowing complex irradiation devices to be inserted and withdrawn;
- a large number of experimental positions of 84 mm with in addition 4 peripheral 200 mm channels for large irradiation devices. Through loop experiments can be installed through penetrations in the top and bottom cover of the vessel;
- a remarkable flexibility of utilization: the reactor core configuration and operation mode are adapted to experimental requirements;
- irradiation conditions representative of those of various power reactor types - neutron spectrum tailoring;
- high neutron fluxes, both thermal and fast (up to 10^{15} n/cm².s).

A beryllium matrix, composed of irregular hollow prisms forming the reactor channels, acts as a moderator. Beryllium becomes brittle and swells under irradiation. Cracking of the beryllium channels occurs by mechanical interaction, so that the whole matrix has to be renewed after an operation time depending on its utilization.

The facility was shut down once already in 1979-1980, to have its beryllium matrix replaced.

After another operation period of 15 years, the second beryllium matrix was reaching its end of life and had to be replaced to allow further operation. Reactor operation was stopped at the end of June 1995 to proceed with an extensive refurbishment programme, including the matrix replacement.

THE BR2 REFURBISHMENT PROGRAMME

The overall refurbishment programme consists of five distinct phases. Phase 1 (completed in 1992) was specifically a survey of the installations and was intended to identify the critical plant items and systems to be studied in detail in Phase 2 (1992-1994). Phase 3 (from 1994 to 1996) addresses the preparatory activities, i.e. mainly the detailed engineering, the procurement of equipment, the set-up of execution procedures and the detailed planning for the next phases.

Phase 4 covered the actual realization of the refurbishment works as planned during the shutdown of the reactor from mid-1995 to early in 1997.

Phase 5 completes the remainder of the refurbishment works which could be deferred until after the restart of the BR2 reactor.

The key issues of the phase 2 programme were risk assessments to verify that the safety goals are met and to define back fitting or upgrading actions, ageing evaluations and inspections to assess the remaining life and to define the mitigation actions needed. From these studies and inspections resulted the refurbishment action plan.

The main aspects of the refurbishment action plan may be classified in three categories:

- modifications,
- inspections,
- maintenance.

All these activities were due to be conducted in the period July 1995 - beginning 1997.

Some non-critical operations were delayed after the restart of BR2 for implementation in 1997 and beyond.

Modifications of the Installations

The refurbishment involved the following important investments:

- Replacement of the Beryllium matrix,
- The reliability enhancement of the isolation valves of the primary circuit**,**
- The reliability enhancement of the ventilation isolation valves of the containment building,
- The partial renewal of the primary process instrumentation,
- The replacement of the control desk in the reactor control room,
- The installation of an emergency control panel outside the containment building,
- A new crane handling system with a capacity of 26 tons for handling critical loads in the process building,
- The installation of new air compressors and the optimization of the distribution network;
- A new fire protection system, including prevention, detection and protection,
- The upgrading of the electrical distribution networks.

On the other hand, a number of minor modifications were introduced

- Most of the neutron beam tubes were shut off in order to reduce the risk of pool leakage,
- The existing demineralized water plant has been put out of service and replaced by mobile ion exchange units,
- The pool heat exchangers have been replaced by new units.

Inspections

The refurbishment included a series of inspections and evaluations required in the frame of the plant lifetime extension project. The most important inspection concerned the aluminium reactor vessel.

The present inspection was important because in-service inspection can only be conducted when the beryllium matrix is unloaded. The prospects for life extension of the vessel were evaluated in the frame of the second and third phases of the refurbishment programme. The life limiting phenomena studied were fracture toughness, low cycle fatigue and corrosion.

An important effort was devoted to the determination of thermal and fast fluences by neutronic calculations and measurements on scrapings recovered on the vessel shroud. Also

theoretical fatigue curves were calculated. Fracture toughness was evaluated by modelling and testing on representative samples from the vessel shroud and samples of various aluminium alloys. It was concluded from these studies that the vessel will remain adequate for the planned 15-year extension period, provided the scheduled inservice inspection reveals no unacceptable defect in the vessel wall, in particular in the beltline welds.

An exhaustive inspection of the reactor vessel took place from June 1 to June 15, 1996. After visual, eddy current and ultrasonic examination of the vessel, it could be concluded that there was no detected degradation since the 1979 inservice inspection.

Maintenance

An extensive overhaul programme of the main mechanical, electrical and cooling components and systems is programmed.

The most important aspects are:

- the complete overhaul of the secondary circuit cooling towers;
- the replacement of damaged secondary pipings;
- the overhaul of the emergency power units;
- the overhaul of the most important valves of the cooling circuits;
- the replacement of the pressurizing system - preheater and pressurizer - of the primary circuit.
- the repair/replacement of seals on penetrations of cooling pipes in the reactor pool.

PRESENT AND FUTURE UTILIZATION OF THE BR2

Survey of Current Programmes

History

Since its early operation in 1963 until about 1989, the BR2 has been extensively used for fuel and materials testing related to the development of "new-generation" nuclear reactors, i.e. the gas cooled (CO_2 and He) thermal reactors, the liquid metal cooled fast breeder reactors (essentially for the SNR 300), the gas cooled fast breeder reactor, the testing of advanced LWR fuels and (to a lesser extent) the testing of fusion reactor materials. Most of the irradiation projects were devoted to the technological and safety problems of

LMFBRs. Beside historical policies, this strategy was also strongly based on the excellent features of BR2 to achieve very high fast neutron fluxes (up to 7.10^{14} n/cm^2.s above 0,1 MeV), to have large experimental volumes (up to ~ 200 mm in length), to easily allow neutron spectrum tailoring and to adapt the operating modes to the experimental requirements.

This quarter of a century period saw a tremendous diversity of dedicated irradiation rigs and forced cooling loops, including complex safety experiments with cooling blockages inside fast reactor fuel bundles and post-accident heat removal experiments on LMFBR core debris beds.

In parallel to these scientific and technological irradiations, the BR2 was also (and still is) heavily used for the production of different radioisotopes for medical and industrial applications.

A Belgian policy decision has ended all R&D efforts on fast neutron reactors in 1989. This caused a drastic strategic turn-around in the utilization of BR2, resulting in renewed focusses on the development of different types of LWR fuels and materials, on LWR safety research and on fusion reactor materials. The isotope business was also extended and the production of neutron doped silicon was introduced.

Light Water Reactor Fuels

For many years SCK•CEN has been involved in different international and bilateral programmes on LWR fuel behaviour and development, both for PWRs and BWRs. Irradiations in BR2 addressed stationary as well as transient regimes, while comprehensive post-irradiation examinations were conducted in the Laboratories for High and Medium Activity. The tested fuels concerned mainly: UO_2, MOX, fuel with burnable poisons (e.g. Gd_2O_3) and fuels with advanced cladding. Both fresh and pre-irradiated rods were irradiated, the latter retrieved from the previous BR3 reactor (PWR type) at SCK•CEN and from commercial power reactors.

Dedicated facilities were designed and installed in BR2 for the LWR fuel programmes and are still operational at present. The main facilities are:

CALLISTO Loop

The CALLISTO facility (CApabiLity for Light water Irradiation in Steady state and Transient Operation) is a specialized high pressure loop offering a comprehensive range of experimental conditions representative of PWR power reactors. Its basic layout allows to irradiate clusters of nine fuel rods (fresh or pre-irradiated) in each of the three in-pile sections, for a total of 27 rods (Benoit, Decloedt et al, 1992).

Normally the rods are about 1 m long, but variants are possible. Each in-pile section could also accommodate three full length PWR rods, i.e. over 4 m long.

Up to now, fuel rods were irradiated in CALLISTO in nominal steady state regime in order to achieve their target burnup. However the loop can also be operated, within certain limits, in off-normal and transient regimes, e.g. power ramping or cycling, cooling mismatch conditions, loss of flow.

PWC/CCD Devices

The Pressurized Water Capsules (PWC) rigs are versatile capsules with pressurized stagnant water in either PWR or BWR conditions. In its present layout a PWC in-pile section can receive one single fuel rod (fresh or pre-irradiated) of about 1 m length, or shorter segments (typically 30 cm fissile stack) which may be instrumented with central thermocouple and/or other scientific sensoring devices (Bodart, De Raedt et al, 1992). A PWC rig is surrounded by a Calibration and Cycling Device (CCD), that incorporates a ^3He screen to perform power cycling or transients. The CCD is also instrumented to achieve precise thermal balance measurements on the fuel rod heating rate.

Many different profiles of power transients, regarding amplitude, ramp rate and holding time, have been realized in the PWC/CCD devices, including power-to-melt tests. Some of these were achieved by ramping the power of the reactor also, to complement the capacity of the ^3He screen.

An extrapolated design of PWC is feasible to accept 4 m long fuel rods, which could previously only be irradiated in a commercial PWR.

LWR Structural Materials

All kinds of materials can be tested in BR2 up to high neutron doses (thermal and/or fast). Current programmes concerned mainly the reactor pressure vessel steel embrittlement mechanisms and Irradiation Assisted Stress Corrosion Cracking (IASCC).

Dedicated rigs have been engineered to irradiate test samples in different environmental conditions: open baskets (cooling of the samples directly by the BR2 primary water), VESTAL rig (specialized device to irradiate vessel steel samples at 290C in inert gas) (Aït Abderrahim, Pouleur, 1992) and also the CALLISTO in-pile sections (with the samples immersed in the PWR type loop water). The latter option demonstrates the versatility of the CALLISTO design which was actually applied to an interesting R&D project in 1995 (CHIVAS project).

Fusion Reactor Materials

The list of fusion reactor materials and components that have already been irradiated in BR2 is quite impressive. Typical examples are given hereunder.

Structural Materials

- First wall materials: mostly different grades of stainless steels. One of these experiments (FAFUMA series) has been the first of its kind and rather unique: it achieved the fatigue testing of samples by cyclic push-pull loading during irradiation until the occurrence of fatigue rupture (Vandermeulen, Hendrix et al, 1991).
- Divertor materials: in particular molybdenum and copper alloys.
- Blanket materials: especially beryllium metal samples.

Teleoperation Materials and Components

Experiments are required to test and qualify, under intensive gamma radiation, specific materials and components to be used on remote handling machines inside the TOKAMAK torus and near the first wall:

- electronic equipment and robotic components (rad-hard electronic circuits);
- optical fibers and optical equipment;
- measuring sensors and instrumentation (force, deformation, ultra-sonic, ...).

These irradiations are done in dedicated facilities and rigs, using the gamma fluxes from either the spent BR2 fuel elements or from intensive ^{60}Co sources.

Commercial Productions

Beside the scientific and technological experiments, the BR2 reactor has always been heavily used for the production of radioisotopes for medical and industrial applications and, more recently, also for neutron transmutation doping of silicon to be used by the semi-conductor industry.

The high neutron fluxes available in the BR2 result in high specific activities for radioisotopes like Ir-192 (≥ 700 Ci/g), Sr-89 (≥ 210 mCi/g) and Mo-99 (≥ 150 Ci/target).

Neutron transmutation doping (N.T.D.) of silicon ingots - up to 5 inches diameter, batch length up to 800 mm - is performed in the SIDONIE rig. About thirty tons were so produced between 1992 and 1995. The SIDONIE rig produces NTD silicon of high quality with a short turn-around time for the customer. High quality means that the target resistivity is met within 2% axially and radially.

Future Utilization

Orientation of Future Programmes

Internal R&D projects at SCK•CEN, aiming at modelling the behaviour and properties of nuclear fuels and materials, will increasingly use the testing capabilities of BR2. In the field of LWR fuels, the objective is to improve the efficiency and safety of MOX utilization and of increased burnup. In particular the issues of fission gas release and thermal conductivity are being investigated. Transient experiments on pre-irradiated and well instrumented fuel rods are essential for that purpose. Special emphasis is also given to the upgrading and extension of in-pile sensors so as to enhance the quality of the experimental output. The existing irradiation devices (CALLISTO, PWC/CCD) are well suited as base facilities in such upgrading process.

Concerning nuclear materials, the internal efforts concentrate on pressure vessel steel embrittlement. Irradiation campaigns in BR2 are ongoing. The ultimate goal is the understanding of the various embrittlement mechanisms and the identification of the main irradiation damage mechanisms, unravelling those which display an incubation fluence from those which are function of the alloy composition, the irradiation temperature, the dose rate, etc. A programme on irradiation assisted stress corrosion cracking (IASCC) of LWR structural components has been started recently and irradiations in the CALLISTO loop are ongoing.

Beside those proper SCK•CEN research programmes, the BR2 stays open for programmes in an international context, involving industry, regulatory bodies and multi-party collaborations.

In order to respond to future safety oriented needs, an advanced water-cooled loop is being studied: a PWR-type integrated loop which could accommodate up to 25 fuel rods, is to be loaded in the central 200 mm flux trap. This loop is designed to perform experiments under realistic PWR conditions as to neutronics, thermohydraulics, water chemistry, etc. The loop could be used for steady-state irradiations as well as for transient tests, on either fresh or pre- irradiated fuel rods. Simulation of accidental control-rod withdrawal and of fuel bundle degradation after severe accidents are among the possibilities. This new device is described in the next paragraph.

Fusion research in Belgium is integrated into the European fusion programme. Irradiations in BR2 will further be concentrated on characterization of structural materials and investigation of irradiation induced degradation of various materials, such as ceramics. A feasibility study for a testing device of integrated blanket modules is being performed. BR2's strengths are the 200 mm channels, its interesting neutronic characteristics and the experience in the operation of large loops.

Gamma irradiation possibilities will be extended to larger test volumes, using a new facility (BRIGITTE) with nearly ∅ 300 mm useful diameter.

Among other devices which could be operated in BR2 is an integrated sodium-cooled loop for testing plutonium-enriched fuel rods under fast neutron reactor conditions, to investigate the accelerated burning of plutonium and the transmutation of the minor actinides.

Obviously the scientific & technological irradiations in BR2 will continue to be supplemented by commercial production activities regarding radioisotopes and NTD-silicon.

Safety Dedicated Devices

Large power excursions and peak transients (like Reactivity initiated Accidents (R.I.A.)) on LWR fuel lead to cladding failure, while severe accidents (like Loss of Coolant Accidents (LOCA)) lead to degradation of the fuel rods and assemblies. Hence the design of the test section for such experiments must cope with all physical effects of the accident sequences and in particular must be able to contain molten fuel and the released fission products. Within this framework the design of the DESTIN loop is performed.

The DESTIN concept is a large in-pile section to be installed in the central channel (∅ 200 mm) of BR2. This position provides the highest neutron fluxes in the reactor with the best symmetry and the smallest flux gradient across the device.

Its central tube (up to 100 mm diameter) may contain a test bundle with 25 fuel rods (5x5 array), possibly with one or several withdrawable absorber rods. An internal integrated primary circuit provides cooling of the fuel bundle, while this circuit in turn is cooled by a secondary loop system which again is the CALLISTO facility. The fuel bundle is completely isolated from the external cooling circuit, allowing to safely contain the degraded fuel debris and fission products.

The two possible uses are investigated for DESTIN: R.I.A. type tests (possible with damage propagation from rod to rod) and severe core degradation accidents.

CONCLUSION

The BR2 has undergone an extensive refurbishment. The programme encompassed various aspects i.e. replacement of the beryllium matrix, studies, inspections, replacements and upgradings to demonstrate and improve the safety and the reliability of the installations for the next 15 years of operation. BR2 was restarted in April 1997 in line with the planning. The current irradiation programmes are continued, including an enhanced contribution of SCK•CEN's proper R&D experiments on LWR fuels and structural materials. These programmes show prospects for international collaboration.

Upgraded in-pile instrumentation and new advanced facilities are being studied, with particular emphasis on safety oriented tests in BR2.

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